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ROTATING DETONATION ENGINE OPERATION (PREPRINT)

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14. ABSTRACT
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Rotating Detonation Engine Operation

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Nomenclature

MdotH2	=	mass flow of hydrogen
MdotAir	=	mass flow of air
PCB	=	Piezoelectric Pressure Sensor
PDE	=	Pulsed Detonation Engine
RDE	=	Rotating Detonation Engine
Φ	=	equivalence ratio

I. Introduction

THE amount of research being conducted in detonation has greatly increased in recent years. One of the detonation concepts currently being researched is the Rotating Detonation Engine (RDE). A RDE engineered and manufactured by Pratt and Whitney Seattle Aerosciences Center was loaned to the Air Force Research Laboratory at Wright-Patterson Air Force Base for further modification and testing. The engine was initially designed to use ethylene and oxygen, but a number of modifications were made to run the engine on hydrogen and air. Changing the engine to run on hydrogen-air was made for safety and practicality reasons, although this modification decreased the detonability of the mixture and increased the cell size.[1]

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After a number of adjustments and changes in configuration, the RDE was able detonate hydrogen-air mixtures in a particular mass flow and equivalence ratio region. After successful and consistent detonations were found for this particular configuration, the engine was tested at increasingly greater air mass flow rates in order to determine the maximum amount of thrust that could be generated by the engine. However, the engine was only able to generate thrust for air mass flows up to 40 lb/min, which generated about 50 pounds of thrust. When the oxidizer was changed to 23% oxygen and 77% nitrogen instead of atmospheric air (21% oxygen, 78% nitrogen, and 1% argon), the engine generated thrust for air mass flows up to 50 lb/min, which generated 65 pounds of thrust. When the oxidizer was changed once again to 24.8% oxygen and 75.2% nitrogen, the engine generated thrusts for air mass flows above 130 lb/min, which generated over 200 pounds of thrust. Although these were the greatest air mass flows that were tested, an upper air mass flow limit was not found for the 24.8% oxygen and 75.2% nitrogen oxidizer.

In the process of determining the greatest air mass flows that produced a detonation for particular configurations, the engine began to contain progressively less steady single detonation waves above 80 lb/min of air flow. As the airflow was increased to 100 lb/min, the engine began to contain two detonation waves for very brief periods of time. Finally, when the air mass flow rate exceeded 115 lb/min, the engine contained two co-rotating detonation waves for the majority of the run. The high speed camera used in the experiments captured images of the single and co-rotating detonation waves in the detonation channel. Figure 1*** shows a few frames of the single detonation wave in the top row and a few frames of the co-rotating detonation waves in the bottom row.

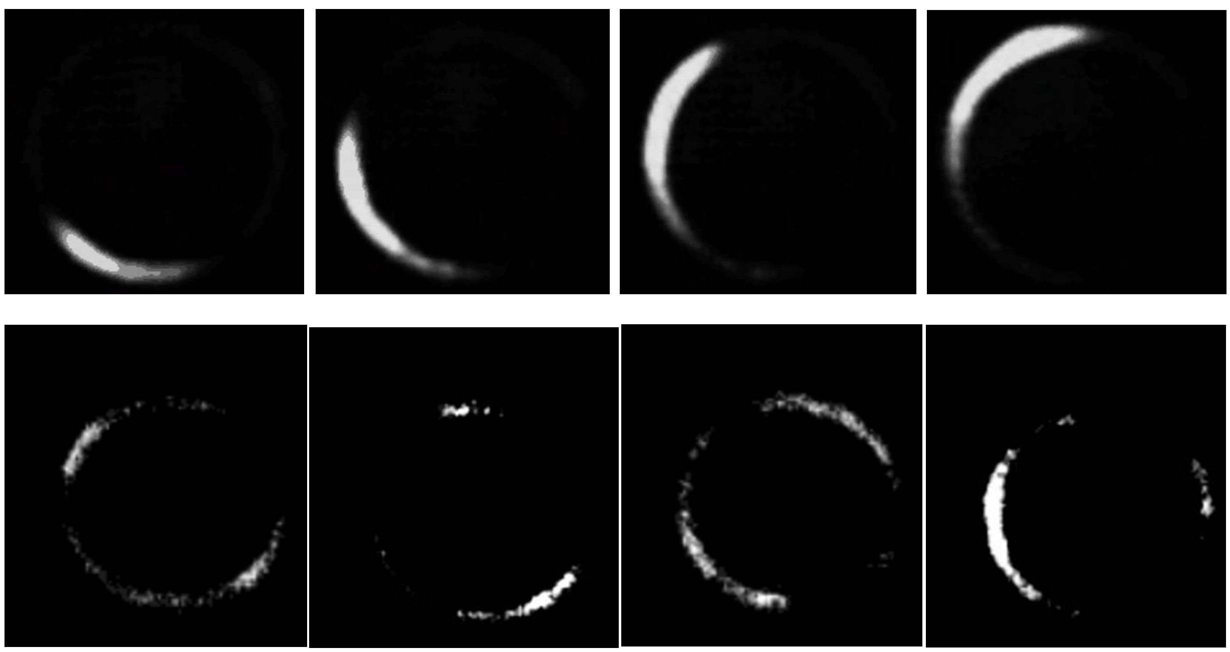

Figure 1. Overhead video of one detonation wave (top row) and two detonation waves (bottom row)

The rotation of the two detonation waves in the bottom row of Figure 1*** shows that the two detonation waves were co-rotating. At times, when two detonation waves existed in the engine they were counter-rotating, but this phenomenon only occurred in a transient state. Whenever two detonation waves were counter-rotating, the inevitable collision of the waves would halt the progress of each wave. This could have occurred because the strong pressure gradient of each wave destroyed the structure of the other wave and halted the detonation combustion reaction, at least for a time. In addition, the detonations could have ceased to propagate through the channel because each detonation wave did not have a detonable mixture to propagate through. After meeting the other wave, the path ahead of each detonation wave would have been devoid of the necessary amount of reactants to continue a detonation combustion reaction since all the reactants had just been consumed by the other wave. In any event, steady two detonation wave combustion only existed in the engine when the waves were co-rotating.

II. Background

The increased efficiency of pressure gain combustion over constant pressure combustion promised by thermodynamics has fueled a surge in detonation research in recent decades. Breakthroughs and improvements have been made, particularly in the field of Pulsed Detonation Engines (PDEs). PDEs have reached a level of safety and reliability that allowed for the first PDE-powered manned flight on January 31, 2008.[2] Although PDEs have made great strides in recent years, some shortcomings still remain. First, constant re-ignition of the detonation tubes results in losses in ignition energy and total pressure each time the mixture in a tube is detonated. Second, the pressure fluctuations in the exhaust gases of a PDE can vary in magnitude up to a factor of 20.[2] Although the atmosphere behind a pure PDE is not bothered by 20 times pressure fluctuations, these pressure fluctuations would cause decreased efficiency and excessive wear to a turbine if a PDE replaced a conventional combustor in a gas turbine engine. Third, a PDE requires time to fill the tube prior to ignition and time to purge the products after the combustion has occurred. The time required to fill and purge the tube after each ignition sequence results in a significant portion of the engine operation cycle that does not produce any thrust. The PDE operating cycle shown in Figure 2*** shows that the fill and purge portions are an inherent part of PDE operation.

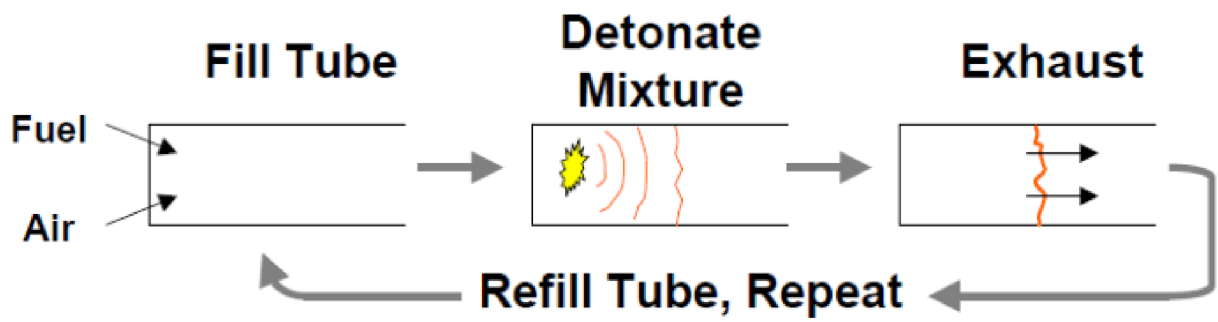

Figure 2. Basic PDE operating cycle[3]

Therefore, researchers have strived to harness the power of detonation in ways that reduce or eliminate the high ignition losses, high outlet pressure fluctuations, and unsteady thrust output of PDEs. One of the new designs was the Rotating Detonation Engine (RDE). An RDE operates by exhausting an initial detonation tangentially into a cylindrical channel that is being continuously filled with a detonable mixture. Since the channel is continuously filled and does not require a purge cycle, the detonation is free to propagate indefinitely in the cylindrical channel as long as the detonable mixture continues to be supplied. This ignition technique eliminates the inefficiencies of constant re-ignition in a PDE. In addition, since the detonation wave is travelling circumferentially along the cylindrical channel and the exhaust gases are travelling axially to the cylindrical channel, the exhaust gases consist of 5:1 pressure fluctuations[2], which is much less than the pressure fluctuations of the PDE. The continuous filling and purging allows an RDE to produce a much more steady output of thrust than a PDE. A thermodynamic CFD simulation of an RDE is shown in Figure 3*** along with a basic schematic of the fuel flow, exhaust flow, and detonation propagation.

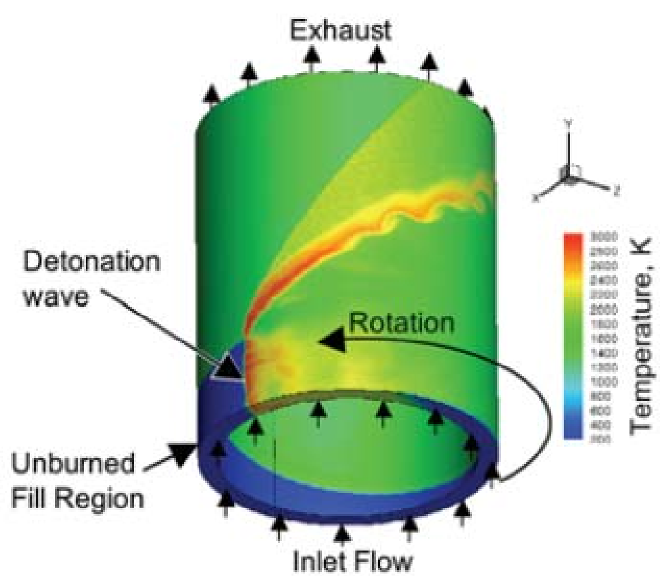

Figure 3. CFD model of an RDE combustion chamber[4]

Since an RDE does not contain any moving parts, the engine relies on pressure gradients in order to continuously fill the detonation channel with a detonable mixture of fuel and oxidizer. This approach has its drawbacks as the detonation results in a pressure increase of 15 times or greater,[4] causing a reverse flow of hot product gases into the fuel and oxidizer manifolds as the detonation wave passes. After the wave has passed, the channel pressure subsides, allowing the flow of fuel and oxidizer into the channel to resume. Not only does the increased pressure from the detonation wave shorten the amount of time that the fuel and oxidizer flow into the channel, the back flow of hot gases into the injection manifolds could cause a reverse propagating flame. For this reason most RDEs do not mix the fuel and oxidizer until they are injected into detonation channel.

III. Setup and Operation

The Pratt and Whitney RDE was originally designed to use ethylene-oxygen for its fuel and oxidizer combination. However, the fuel-oxidizer combination was changed to hydrogen-air for safety and practicality reasons. Switching the oxidizer from oxygen to air greatly improves the safety of the setup since pure oxygen can ignite inside a supply line and cause a fire or explosion if a pressure surge occurs, especially in the presence of oils. Secondly, the use of air as the oxidizer in a combustion reaction is much more practical than pure oxygen as it allows an engine to use the atmosphere as an oxidizer instead of the oxidizer being carried in the aircraft. Even though the new oxidizer-fuel combination was a good modification for safety and practicality reasons, the combination increases the difficulty of running the detonation engine properly. Hydrogen-air is a more difficult fuel-oxidizer combination to use in a detonation engine than ethylene-oxygen because the detonation cell size of hydrogen-air is usually 10 to 20 times greater than the detonation cell size of ethylene-oxygen[1], depending on the conditions. The initial detonation used for igniting the detonation in the channel was created by a predetonator inserted tangentially into the detonation channel. The predetonator uses a hydrogen-oxygen mixture where microsolenoids control the flow of both species as they are fed separately into a small chamber. The detonable mixture was then ignited by an automotive spark plug, and exhausted into the continuous flow of hydrogen and air in the detonation channel. The predetonator only fired once for each run, making the amount of hydrogen and oxygen consumed by the predetonator too small to be significant.

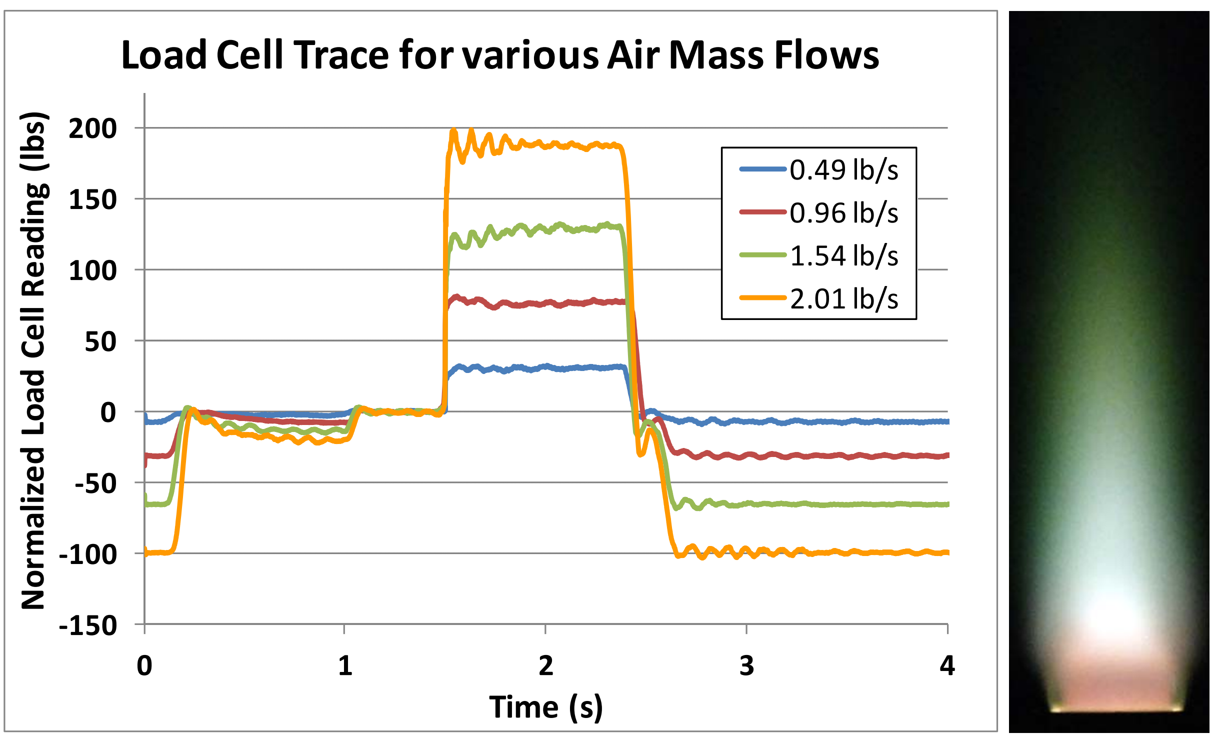

Figure 4. Normalized load cell readings at various air mass flows with a side view image of a successful detonating run

The hydrogen flow and air flow to the engine are controlled by a series of pneumatic valves actuated by a computer control program. The hydrogen and air both flowed into the channel for a designated period of time before the ignition, and a designated period of time after the ignition. The total time of the run was determined by the length of time both the hydrogen and air continue to flow into the channel after the ignition. Usually the fuel supply was closed first, which caused the combustion to cease 0.15-0.25 seconds after the end of the fuel flow time. The mass flows of both the hydrogen and the fuel were determined by pressure readings upstream and downstream of critical nozzles. The engine is attached to three outside poles by pillow blocks, allowing it to move up and down uninhibited. To measure the thrust of the engine, a load cell was placed between the bottom of the engine and the platforms it rests upon. Although this placement of the load cell was effective for determining the thrust of the engine, its location gravitationally below the engine added the weight of the engine to its baseline reading. In addition to the weight of the engine, the fuel and oxidizer flows into the engine also affected the load cell reading. Fortunately, the oxidizer flow into the engine began 1.5 seconds before ignition and the fuel flow into the engine began 0.5 seconds before ignition. This left 0.5 seconds for the load cell to collect data at a steady condition before the thrust from the detonation began. Therefore, in order to calculate the thrust generated by the engine, the average load cell reading 0.4 to 0.1 seconds before ignition was subtracted from the average load cell reading between a tenth of a second after ignition and a tenth of a second prior to shutdown. These averages were taken one tenth of a second before and after a flow change or ignition event in order to help alleviate any transient effects on the averages. In addition to determining the amount of thrust generated by the detonation, the average load cell reading from 0.4 to 0.1 seconds before ignition was subtracted from every value recorded by the load cell during the run in order to set a zero point for graphically comparing the thrust generated by the detonation for different runs. This concept is shown in Figure 4***, where the load cell reading of all four runs have been normalized by each run's average reading 0.4 to 0.1 seconds before ignition.

The final measurement for the RDE was the calculation of the detonation wave speed propagating through the detonation channel. One of the methods used to measure the detonation wave speed was by recording video viewing directly into the detonation channel. The camera used in the experiment was a high-speed camera recording at 50,000 frames per second with a 15 μs exposure time. The product of the frame rate and the circumference of the channel was divided by the number of frames required for the detonation to complete a lap around the engine to determine the velocity of the detonation (Equation 1)***. Although this method was a quick way to check the average velocity of a detonation wave during one lap around the detonation channel, the thousands of laps achieved during a typical run made this method inadequate for determining the average detonation wave speed for an entire run.

$$\frac{(Camera\ Frame\ Rate)\pi d_{chan}}{Number\ of\ Frames\ in\ Lap} \tag{1}$$

The other method for calculating the detonation wave speed in the channel was by using Piezoelectric Pressure Sensors (PCBs) placed in the outer shell of the detonation channel. The voltage output from the PCBs was collected at 1 or 2 MHz for the entire duration of the run. The PCBs would record a sharp pressure rise when the detonation reached the sensor, then quickly fall off as the detonation moved away from the port where the PCB was located. This pressure pattern repeated itself thousands of times per run as the detonation made thousands of laps around the channel. The PCB pressure trace for 3ms of a run is shown in Figure 5*** along with the

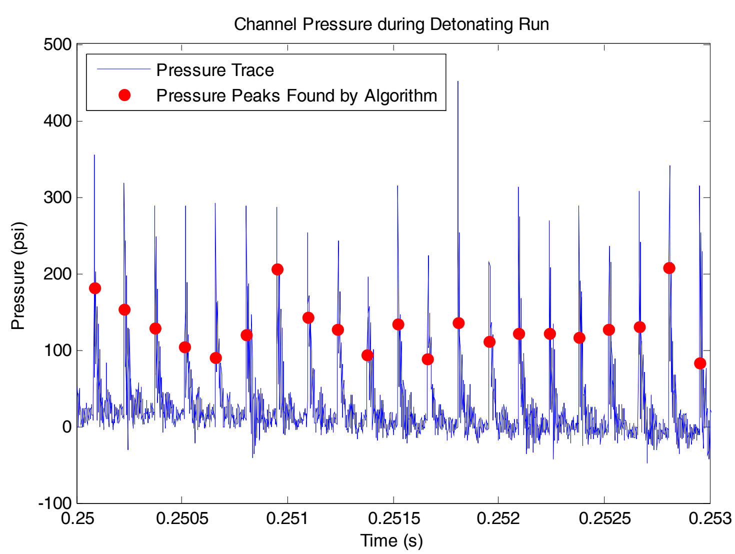

Figure 5. PCB pressure trace with peaks found by a computer algorithm

pressure peaks found by a computer algorithm. Since a run contained thousands of pressure peaks, a computer algorithm was devised to determine the total number of pressure peaks in the PCB data and the time that each peak occurred. This algorithm allowed the average wave speed of the detonation to be reported for the entire run. The average wave speed was calculated by dividing the product of one less than the number of peaks found and the circumference of the channel by the difference in time between the last pressure peak and the first pressure peak (Equation 2)***. Another calculation obtained from the PCB data was the unsteadiness of the detonation wave. The unsteadiness of the detonation wave was defined as the standard deviation of the time elapsed between all the pressure peaks.

$$\frac{(Number\ of\ Pressure\ Peaks - 1)\pi d_{chan}}{t_{last\ pressure\ peak} - t_{first\ pressure\ peak}} \tag{2}$$

IV. Results

The tests that were performed characterized the wave speed, wave unsteadiness, and thrust as the engine progressed from having one detonation wave propagating through the engine to having two detonation waves propagating through the engine. This progression from one detonation wave to two detonation waves occurred as the air mass flow into the engine was increased. However, this transition from one to two detonation waves was not a seamless process where the engine suddenly began having two detonation waves instead of one above a certain air mass flow. Instead, as the air mass flow increased nearer to the point of two wave operation, the unsteadiness of the single detonation wave began to increase.

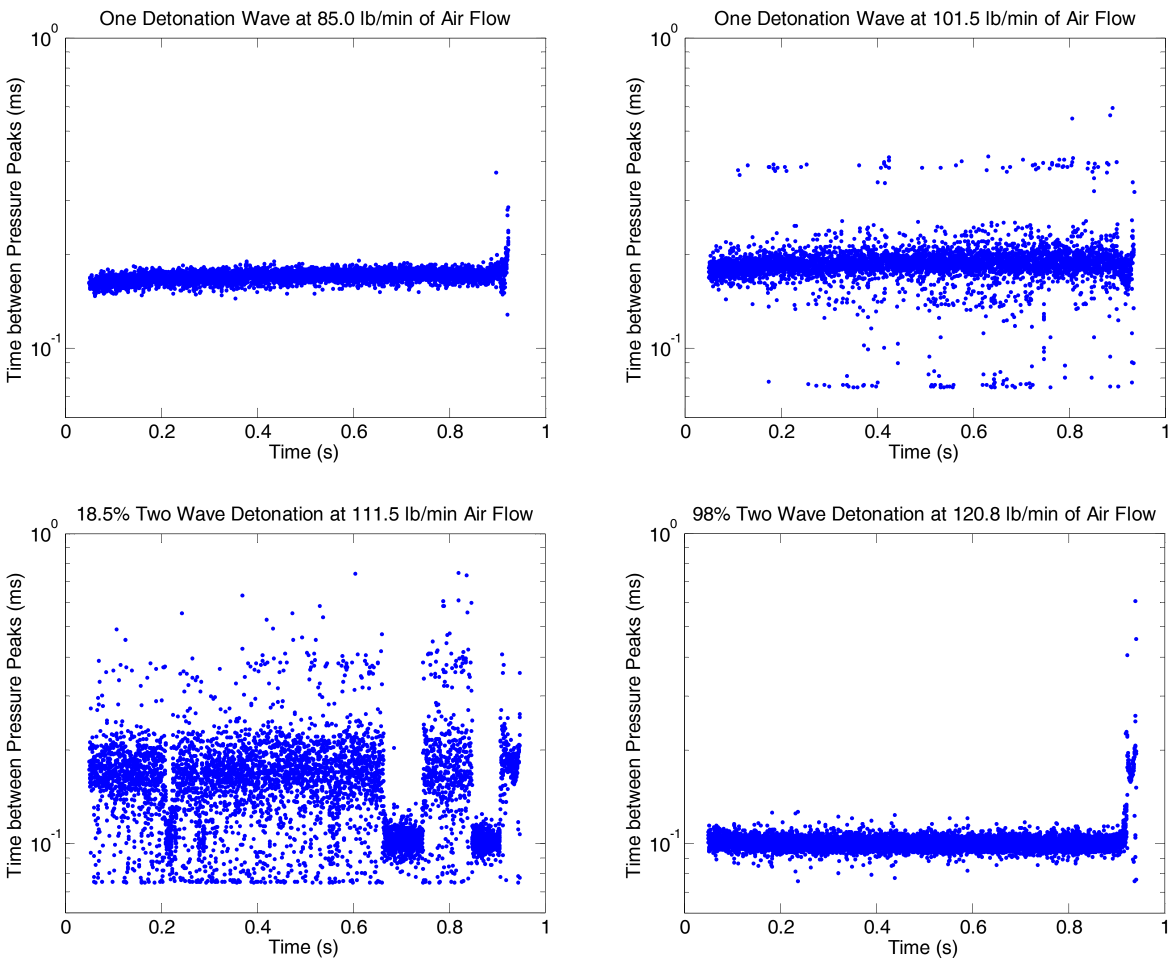

Figure 6. Lap Times during One to Two Wave Transition: The time elapsed between pressure peaks in milliseconds plotted logarithmically as a function of when the peaks occurred in seconds.

For a given engine configuration and fuel/oxidizer combination, the runs fell into one of three groups depending on the air mass flow rate of the run. At the lowest air mass flow rates, the engine only contained one steady detonation wave. As the air mass flow rate increased above a particular value, the engine began to contain two detonation waves at some points during the run, but overall the run was predominantly one wave operation. As the air mass flow increased further, the engine transitioned to predominantly two wave operation with some one wave operation. The four plots shown in Figure 6*** plot the time between each pair of pressure peaks on a logarithmic scale as a function of the average of the times when each pressure peak occurred. The first plot at 85.0 lb/min of air flow depicts a very steady single detonation wave since the lap time for the detonation wave varied very slightly from lap to lap. The second plot at 101.5 lb/min of air flow shows a single detonation wave at an average lap time (and therefore wave speed) very near to the 85.0 lb/min run, but with much greater variation in the lap times. The third plot at 111.5 lb/min of air flow shows one wave operation near the same average velocity as plots one and two for 81.5% of the run, but with even greater variation in the lab times. The other 18.5% of the run in the third plot contains two detonation waves, which were present during the time periods where the average time between the pressure peaks nearly cut in half. The fourth plot at 120.8 lb/min of air flow shows very steady two wave detonation with an average lap time very similar to the portion of the third plot containing two detonation waves.

An interesting result of this testing was the fact that none of the test runs sustained two detonation waves for the entire run. This result was due to the fact that every run, even the runs that predominantly contained two steady detonation waves, concluded with a period of one wave operation. The ending of the run always contained one wave because the flow of fuel and air into the engine was not stopped instantaneously, creating a period of time where the mass flow into the engine was decreased but had not completely shutoff. This lower mass flow caused the combustion reaction to degrade from two detonation waves to one detonation wave. For runs that were predominantly two wave operation before the shutdown sequence, the one wave activity was relatively brief as it only occurred during the last 10 to 30 ms of the run. The one wave activity during the shutdown of a predominantly two wave run can be easily seen in plot D of Figure 6***.

The plots in Figure 6*** are individual snapshots of the transition process from one to two detonation wave operation in the RDE with an increase in air mass flow. Although these plots provide an effective visual description of the wave transition region, the transition is more rigorously described by quantifying the wave unsteadiness of the plots in Figure 6*** and other tests run in the transition region by computing the standard deviation of the lap times. The unsteadiness of the predominant wave form in the run in microseconds was plotted as a function of the air mass flow in pounds per minute in Figure 7.*** The data in this figure is separated into three groups based on the wave activity that occurred during the test. The blue diamonds are the runs that contained only one detonation wave. The red squares are the runs that contained both one and two detonation waves, but predominantly contained one detonation wave. The green triangles are the runs that contained both one and two detonation waves, but predominantly contained two detonation waves. The points in Figure 7*** that were shown in greater detail in Figure 6*** are labeled accordingly.

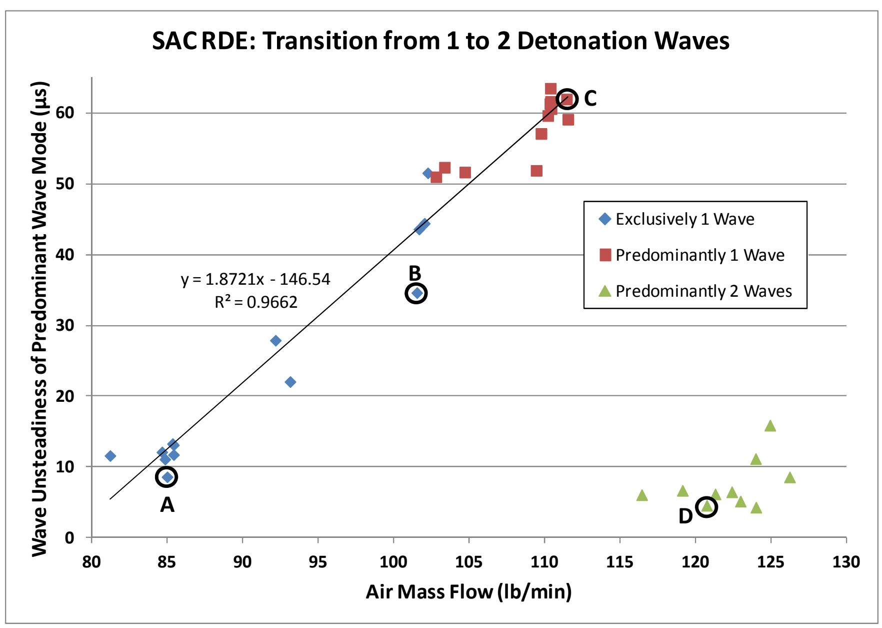

Figure 7. Wave Unsteadiness in One to Two Wave Transition Region

The tests in Figure 7*** show that the increasing unsteadiness of the single detonation wave with increases in air mass flow shown in plots

A, B, and C of Figure 6*** have a linear relationship. Although some variation occurred in this linear trend, the high R^2 value indicates that the fit is quite accurate. After the engine transitions to predominantly two wave operation above 115 lb/min of air flow, the unsteadiness of the two wave detonation is very similar to the unsteadiness of the most steady single detonation wave runs. This sharp drop in the unsteadiness of the predominant wave form in the engine at air mass flows above 115 lb/min shows that the engine is capable of steady operation at higher air mass flows by establishing additional detonation waves.

Although the engine is able to produce non-ideal detonation waves through the one to two wave transition region, greater unsteadiness of the detonation wave and therefore the combustion process had adverse effects on the specific thrust generated by the engine. These effects are shown in the plot of specific thrust as a function of air mass flow in Figure 8***. Figure 8*** contains four different groups of data. The blue diamonds are runs with a gross injection area of 0.123 in^2 that exclusively contained one wave, the red squares are runs with a gross injection are of 0.227 in^2 that exclusively contained one wave, the green triangles are runs with a gross injection area of 0.227 in^2 that contained both one wave and two waves at different times during the run, but predominantly contained one wave, and the orange circles are runs with a gross injection area of 0.227 in^2 that contained both one wave and two waves at different times during the run, but predominantly contained two waves.

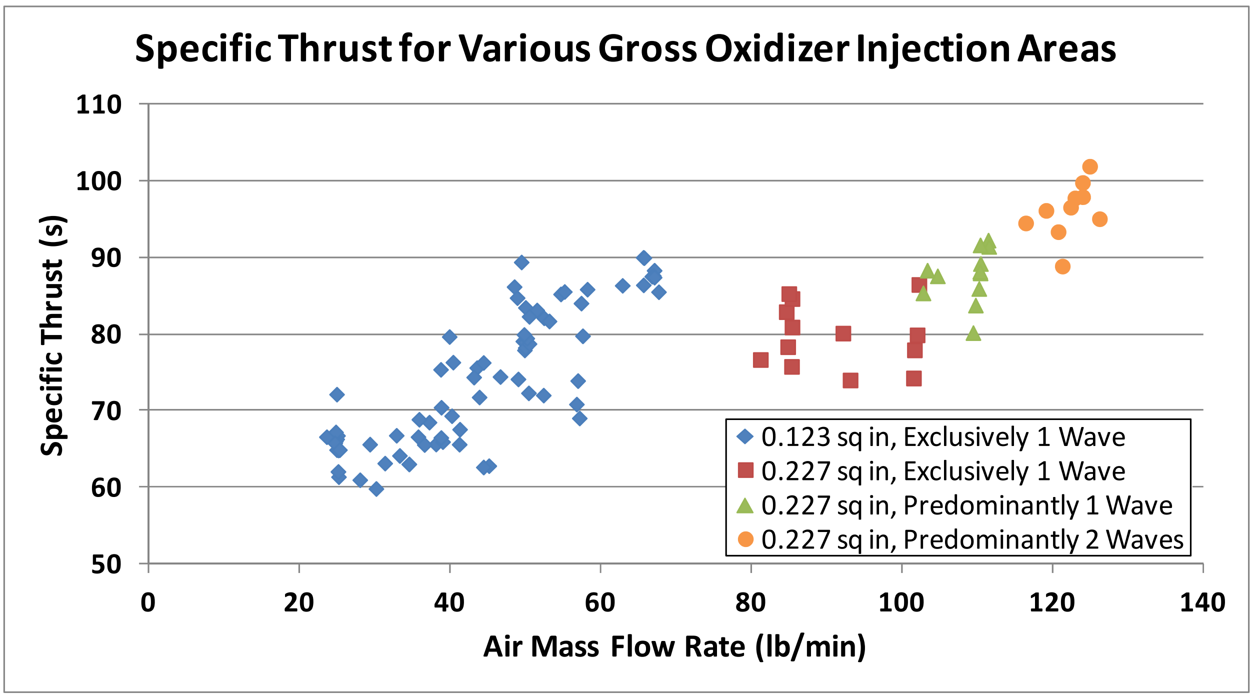

Figure 8. Specific thrust of the RDE versus the air mass flow rate.

The data set in Figure 8*** that includes runs with a gross injection area of 0.123 in^2 and exclusively one detonation wave show a linear trend between specific thrust and air mass flow into the engine. However, this trend did not hold when the air mass flow was increased to the transition region from one to two detonation waves. The specific thrust for the runs with a gross injection area of 0.227 in^2 and exclusively one detonation wave remained constant as the air mass flow into the engine was increased. When the engine began to contain two detonation waves, the specific impulse resumed its trend of increasing linearly with an increase in air mass flow. This data suggests that the unsteady combustion that occurs at air mass flows slightly below the onset of two wave activity is less efficient than the combustion reaction that creates one or two steady detonation waves.

Although the specific thrust began to increase once again when the engine began to contain two detonation waves, about half of the predominantly one wave runs that also contained two waves did not exceed the greatest specific thrust of the exclusively one waves runs at slightly lower air mass flows. This was likely the case because about 85% of the predominantly one wave runs had two detonation waves for less than 10% of the run time, and all had two detonation waves for less than 20% of the run time, as shown in Figure 9***. Even though these predominantly one wave runs had some two wave detonation combustion, since the majority of the run was very unstable one wave detonation (as shown in Figure 7***), the specific thrust did not increase as rapidly with air mass flow as the predominantly two wave runs.

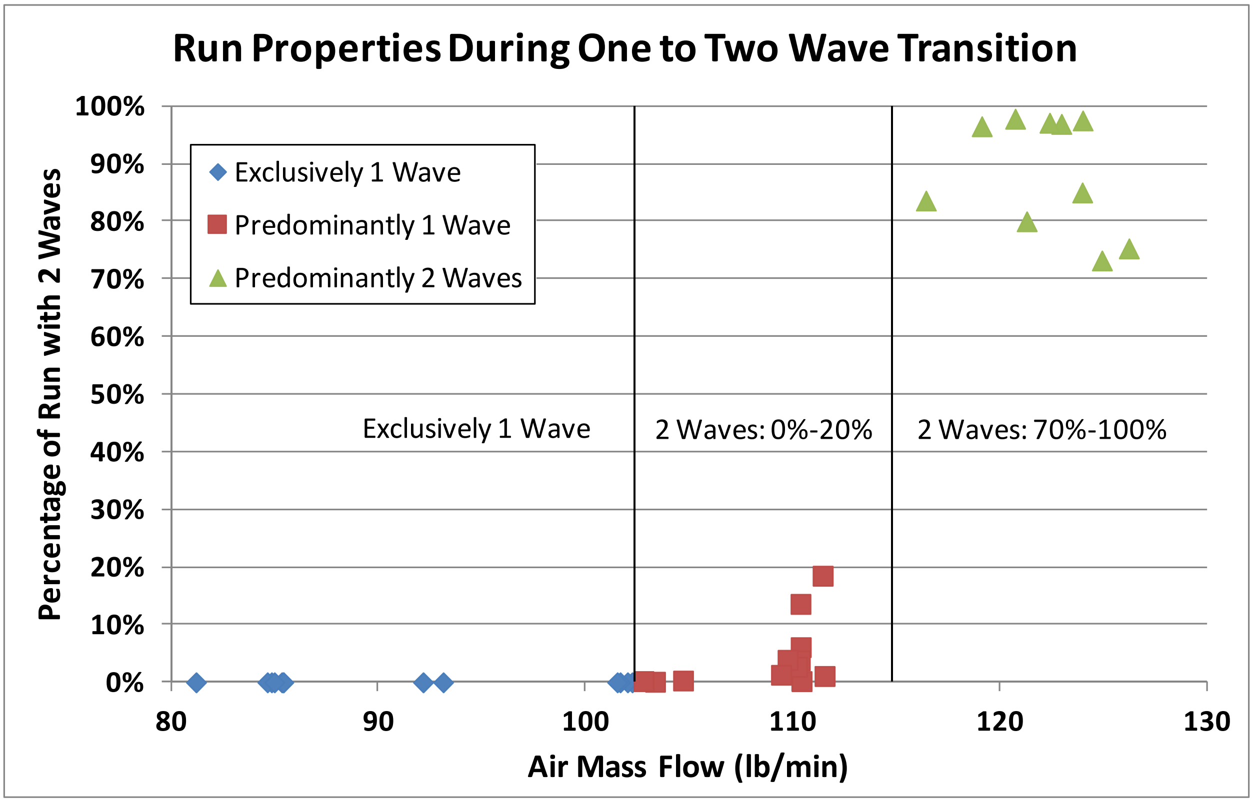

Figure 9. Percentage of run time that contained two detonation waves as a function of air mass flow

The data in Figure 9*** show that the transition from exclusively one detonation wave runs to predominantly one detonation wave runs, as well as the transition from predominantly one detonation wave runs to predominantly two detonation wave runs occurred at a particular threshold of air mass flow. The transition from exclusively one detonation wave to predominantly one wave detonation occurred between 102.2 lb/min and 102.7 lb/min of air mass flow, an increase of less than half of a percent. The transition from predominantly one wave detonation to predominantly two wave detonation occurred over a larger air mass flow range of 111.5 lb/min to 116.5 lb/min, an increase of less than 5%. In addition to the rapid and precise transition between different operating modes of the engine, it is important to note that all of the predominantly one wave runs contained two detonation waves for less than 20% of the run, while all of the predominantly two wave runs contained two detonation waves for greater than 70% of the run. This lack of a smooth transition between the two regions containing two waves could have been the case because the transition region between predominantly one wave runs and predominantly two wave runs occurs over a very small air mass flow region that would contain a more equal split between one detonation wave and two detonation wave activity. On the other hand, the absence of a run with about 50% two wave activity could have occurred because a particular property of the engine makes it averse to containing a relatively even amount of one wave and two wave detonations.

V. Summary

The rotating detonation engine originally designed by Pratt and Whitney's Seattle Aerosciences Center was loaned to the Air Force Research Lab at Wright-Patterson Air Force Base for further testing and modification. After the engine was reconfigured to use hydrogen and air instead of the original design of ethylene and oxygen, testing began to find a region where the engine could sustain a detonation. After the region of operability with atmospheric air and hydrogen was established, air enriched to 23% oxygen and then 25% oxygen were used as the oxidizer to investigate the effects of the higher oxygen content on the operation range and the thrust output.

As the engine was tested at greater and greater air mass flows with the more detonable mixture of hydrogen and oxygen enriched air, the single detonation wave in the engine became less steady, and then began to split into two detonation waves during a portion of the run. As the air mass flow was increased further, the runs began to contain primarily two detonation waves. The instability of the predominant wave mode of the run grew as the air mass flow entered the transition region, but then sharply fell after the engine began to operate with predominantly two detonation waves. The steadiness of the two detonation waves during predominantly two detonation wave runs was as steady as the exclusively one wave runs before the transition region. The specific thrust output of the engine, which had been increasing linearly with air mass flow, remained fairly constant as the engine entered the transition region between one and two detonation waves, then began to rise linearly with air mass flow once again as the engine began to contain two steady detonation waves for the majority of the run. The transition from exclusively one detonation wave to predominantly one detonation wave and from predominantly one detonation wave to predominantly two detonation waves occurred at particular air mass flow thresholds.

VI. Acknowledgements

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